AGU PUBLICATIONS

Journal of Geophysical Research: Space Physics

Supporting Information for

Magnetic Reconnection inside a Flux Transfer Event-like structure in Magnetopause Kelvin-Helmholtz Waves

R. Kieokaew[1, 2], B. Lavraud[1], C. Foullon[2], S. Toledo-Redondo[1], N. Fargette[1], K.-J. Hwang[3], K. Malakit[4], D. Ruffolo[5], M. Øieroset[6], T. D. Phan[6], H. Hasegawa[7], S. Fadanelli[1,8], L. Avanov[9,10], J. Burch[3], D. J. Gershman[9,10], B. Giles[9], J. Dorelli[9], V. Genot[1], C. Jacquey[1], T. Moore[9], W. Paterson[9], C. Pollock[9], A. Rager[9], Y. Saito[7], J.-A. Sauvaud[1], C. Schiff[9], Y. Vernisse[1], and E. Penou[1]

[1] Institut de Recherche en Astrophysique et Planetologie, Universite de Toulouse, Toulouse, France
[2] CGAFD, Mathematics, CEMPS, University of Exeter, UK
[3] Southwest Research Institute, San Antonio, TX, USA
[4] Department of Physics, Faculty of Science and Technology, Thammasat University, Pathum Thani, Thailand
[5] Department of Physics, Faculty of Science, Mahidol University, Bangkok, Thailand
[6] Space Sciences Laboratory, Berkeley, CA, USA
[7] Institute of Space and Astronautical Science, JAXA, Sagamihara, Japan
[8] Physics department, University of Pisa, Pisa, Italy
[9] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[10] University of Maryland, College Park, MD, USA

Contents of this file

Introduction

In this supplementary information, we focus on the KH-associated magnetopause (MP) current sheets (CSs) during 20:00 and 20:15 UT on 5 May 2017 observed by MMS 1, as marked in Figure 3 of the main paper. We give in Table S1 the details about reference frame determinations for the main magnetopause CSs and the FTE central CS using the minimum variance analysis (MVA) (Sonnerup and Cahill, 1967) and the hybrid MVA method (Phan and Gosling, 2013). We also include Figure S1 to show the main properties of the magnetopause CS prior to the FTE and the FTE CS itself, at a scale that permits to clearly identify them as separate current sheets.

Table S1 gives details of the transformation from GSE to the LMN coordinates using the MVA and the hybrid MVA methods. The MVA method is applied for the CS intervals as marked in between the solid vertical blue lines in Figure S1 (labelled CS3). The first, MP CS interval is chosen to include the magnetic rotation (mainly seen in Bx component) that occurs at about the same time as plasma density and temperature transitions, as expected for the MP. The begin and end times of the CS is chosen such that the magnetic field values outside the region become fairly asymptotic. The centre time of the CS is chosen when *Bx* = 0 during the *Bx* transition from negative to positive values. We give beginning, centre, and end times of the CSs marked in Figure 3 of the main paper in Table S1; they are labelled as CS1, CS2, CS3, and CS4, respectively. We also give the same information for the central CS of the FTE, called FTE-CS, in Table S1 for comparison. For each CS, we give the maximum, intermediate, and minimum variance directions obtained from the MVA. The quality of the variance directions can be assessed from the ratios of the eigenvalues (e.g., Siscoe and Suey, 1972). The eigenvalue ratios in Table S1 indicate overall reliable results except for CS3 in which the determination of the minimum variance direction (λ_3/λ_2) is poor. It is consistent with the fact that it has the most different MVA frame orientation compared to the others (CS1, 2 and 4). The hybrid method, however, does not suffer from this and provides an orientation that is consistent with all other estimates (MVA and hybrid MVA for all other main CS1, 2, and 4 estimates).

For the hybrid MVA method, the normal of the CS is obtained from $\boldsymbol{N} = \pm\langle \boldsymbol{b}_1\rangle \times \langle \boldsymbol{b}_2\rangle / |\langle \boldsymbol{b}_1\rangle \times \langle \boldsymbol{b}_2\rangle|$ where $\langle \boldsymbol{b}_1\rangle$ and $\langle \boldsymbol{b}_2\rangle$ are the 5-second time average of the asymptotic magnetic fields before and after the CS interval, respectively, the sign of $\boldsymbol{N}$ is chosen such that it is directed away from Earth. A first maximum variance direction $\boldsymbol{L}_1$ is obtained from the maximum variance direction of the MVA applied for the CS interval. The $\boldsymbol{M}$ component is then computed from $\boldsymbol{N} \times \boldsymbol{L}_1$. Finally, $\boldsymbol{L}$ is calculated from $\boldsymbol{M} \times \boldsymbol{N}$ so that the local CS LMN coordinates are orthonormal. Note that for the FTE-CS, we use only 1-second time average for the asymptotic magnetic fields because the CS and its asymptotic intervals are short compared to the MP CSs. The normal directions $\boldsymbol{N}$ of all the CS determined from the hybrid MVA are consistent with the minimum variance direction determined by the MVA method except for the CS3 as mentioned above.

From Table S1, one can see that the MVA and the hybrid MVA methods give consistent results. For the normal directions of the MP CSs (CS1 – CS4), both methods yield approximately $-Y_{GSE}$ directions. However, the normal direction of the FTE-CS is mainly in $+X_{GSE}$ direction.

To appreciate difference in local properties of the FTE-CS compared to other MP CSs, we show Figure S1, which is similar to Figure 4 of the main paper but with an extended time interval to include the CS prior to the FTE and the FTE-CS itself. One can see that, at the CS3, the magnetic field, ion density and temperature, are gradually changing as expected for the MP. In contrast, the changes at the FTE-CS are overall smaller and more transient and localised. The current structure of the FTE-CS is localised and strong in magnitude compared to that of the CS3. The current density from both curlometer and FPI-based based current show consistent results. The analysis of the normal directions using the hybrid MVA show that the normal of the CS3 is $[0.24, -0.95, -0.22]_{GSE}$, which is also mainly in $-Y_{GSE}$ direction (as for the other main MP CS 1, 2, and 4) while again that of the FTE-CS is $[0.89, 0.10, -0.45]_{GSE}$ is rather orthogonal and mainly in $+X_{GSE}$ direction.

Table S1. Central, beginning, and end times of the MP CSs (first column) identified between 20:00 and 20:15 UT during the KH event on 5 May 2017 together with their transformations using the MVA (second column) and the hybrid MVA (third column) methods. The central times of the CSs are identified at the *Bx* = 0 crossing time during their transition from negative to positive (see Figure 3 of the main paper). The CS beginning and end times are chosen such that outside the CS the magnetic fields are fairly asymptotic. The maximum, intermediate, and minimum variance directions are given for the MVA method, with the corresponding maximum to intermediate eigenvalue ratio (λ_1/λ_2), and the minimum to intermediate eigenvalue ratio (λ_3/λ_2). Finally, the L, M, N coordinates are determined using the hybrid MVA method. All the transformations are given in the GSE coordinates.

CS numbers / times	MVA (Sonnerup and Cahill, 1967)	Hybrid MVA (Gosling and Phan, 2013)
1) CS time: 20:02:15.4 beginning time: 20:02:12.7 end time: 20:02:18.5	Max var dir = [0.950, 0.195, -0.242] Int var dir = [0.136, 0.440, 0.887] Min var dir = [0.280, -0.876, 0.392] $\lambda_1/\lambda_2 = 5.1$, $\lambda_3/\lambda_2 = 0.23$	L = [0.963, 0.044, -0.214] M = [0.202, 0.192, 0.948] N = [0.084, -0.98, 0.18]
2) CS time: 20:05:15.8 beginning time: 20:05:04.2 end time: 20:05:18.5	Max var dir = [0.917, 0.348, 0.196] Int var dir = [0.106, -0.686, 0.720] Min var dir = [0.385, -0.640, -0.666] $\lambda_1/\lambda_2 = 8.5$, $\lambda_3/\lambda_2 = 0.27$	L = [0.914, 0.356, 0.194] M = [-0.241, 0.093, 0.966] N = [0.326, -0.93, 0.171]
3) CS time: 20:06:42.0 beginning time: 20:06:38.0 end time: 20:06:46.2	Max var dir = [-0.939, -0.274, -0.209] Int var dir = [-0.317, 0.925, 0.210] Min var dir = [-0.135, -0.263, 0.955] $\lambda_1/\lambda_2 = 38$, $\lambda_3/\lambda_2 = 0.62$	L = [0.967, 0.153, 0.156] M = [-0.08, -0.41, 0.898] N = [0.205, -0.897, -0.391]
4) CS time: 20:09:48.6 beginning time: 20:09:45.5 end time: 20:09:50.3	Max var dir = [0.943, 0.305, -0.131] Int var dir = [0.081, 0.169, 0.982] Min var dir = [0.322, -0.937, 0.135] $\lambda_1/\lambda_2 = 56$, $\lambda_3/\lambda_2 = 0.33$	L = [0.953, 0.273, -0.127] M = [0.091, 0.141, 0.985] N = [0.287, -0.952, 0.109]
FTE-CS time: 20:06:51.2 beginning time: 20:06:50.0 end time: 20:06:52.4 (only take 1-s interval for asymptotic value averages)	Max var dir = [-0.295, 0.950, -0.101] Int var dir = [0.509, 0.245, 0.825] Min var dir = [0.809, 0.192, -0.556] $\lambda_1/\lambda_2 = 35$, $\lambda_3/\lambda_2 = 0.08$	L = [-0.175, 0.965, -0.145] M = [0.32, 0.196, 0.918] N = [0.93, 0.116, -0.349]

Figure S1: MMS1 measurements on 5 May 2017 between 20:06:15 and 20:07:15 UT in GSE coordinates. From top to bottom, we show the magnetic field, ion number density, ion parallel and perpendicular temperatures, total, magnetic, and plasma pressures, current density from the curlometer and the FPI-based current at MMS1, respectively. Vertical blue solid lines mark the extents of the CSs. Vertical blue dashed lines mark the centres of the CS, at 20:06:42 UT and 20:06:51.2 UT for CS3 and FTE-CS in Table S1, respectively. One can see that the *Bx, By* (first panel) along with other properties at CS3 have gradual transitions while those of FTE-CS are different and more abrupt/transient.